National Aeronautics and Space Administration

Opportunities and Strategies for Testing and Infusion of ISRU in the Evolvable Mars Campaign

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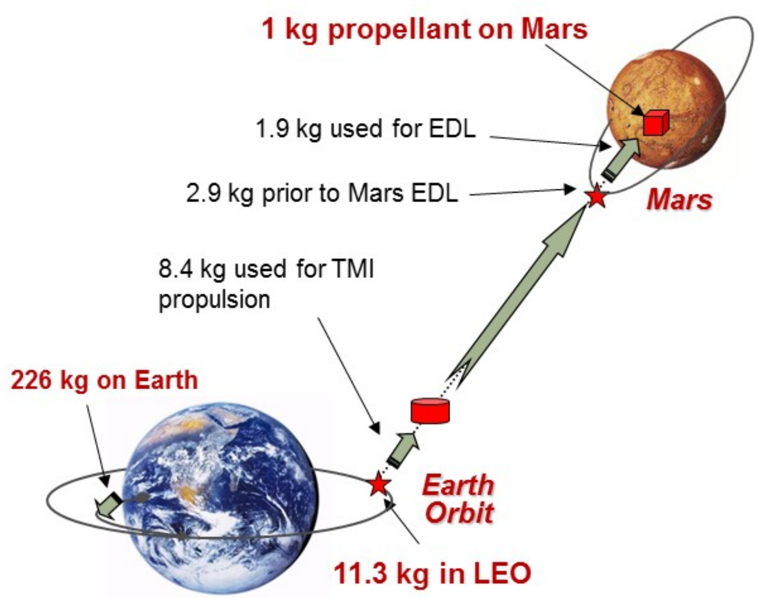
Why consider ISRU? A DRA 5.0 example…

For a Mars mission…

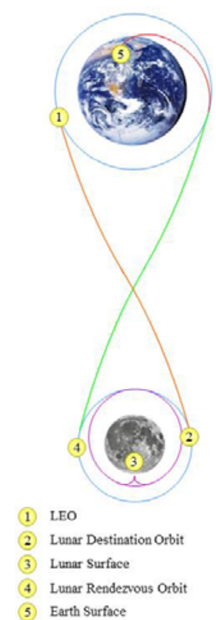
Oxygen only:	75% of ascent propellant mass; 20 to 23 mT
Methane + Oxygen:	100% of ascent propellant mass: 25.7 to 29.6 mT

Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO

Potential 334.5 mT launch mass saved in LEO
= 3 to 5 SLS launches avoided per Mars Ascent



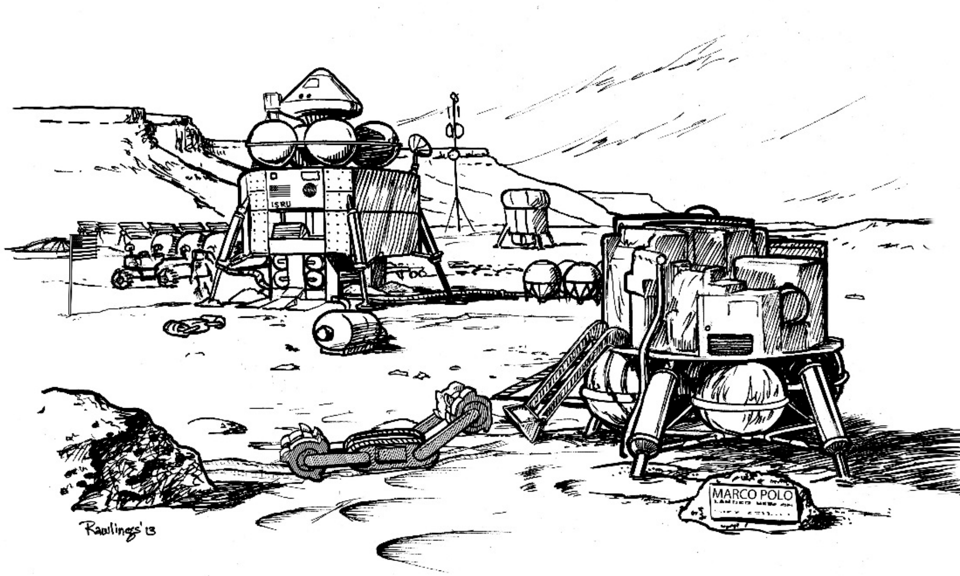
Estimates based on Aerocapture at Mars



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	9.0 kg	183.6 kg
Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample)	12.0 kg	244.8 kg
LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage)	14.7 kg	300 kg
LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew)	19.4 kg	395.8 kg

Evolution of ISRU

- **Solar**
  - **Solar panels** enable on-board and destination power, as well as high Isp propulsion
  - Space-based solar power could increase surface capabilities
- **Gravitational ISRU**
  - **Gravity assists** at the Moon or Mars reduce propellant requirements from Earth
- **Atmosphere**
  - Aerobraking, aerocapture, and **aerodynamic** EDL reduce propellant requirements from Earth
  - **Carbon dioxide** (95%) and **nitrogen** (3%) can be acquired and used on Mars
- **Surface**
  - **Water** resources in the regolith and subsurface permit propellant (methane and oxygen) and consumable (water, oxygen, food, nitrogen) manufacture
  - **Regolith** can provide bulk materials, radiation shielding, and refined resources
  - Use in-situ manufacturing to reduce logistics needs from Earth



The Three Phases to ISRU

- **Prospect**
  - Evaluate potential resource locations:
    - Quantity: *how much of the resource exists*
    - Accessibility: *how to get to and from the resource*
    - Environment: *temperature, pressure, gravity, lighting, radiation*
  - Demonstrate critical technologies, functions, and operations
  - Evaluate environmental impacts and long-term operation on hardware:
    - *dusty/abrasive/electrostatic regolith*
    - *radiation/solar wind*
    - *day/night cycles*
    - *polar shadowing*
- **Test**
  - Perform critical demonstrations at scale and duration to minimize risk of utilization
  - Obtain design and flight experience before finalizing human mission element design
  - Potentially pre-deploy and produce product before utilization
- **Utilize**
  - Make products at scale to be used
  - Integrate ISRU system with supporting systems (*power, storage, controls*)

Prospect

- **Exploration to find the resources needed to enable production**
  - Understanding physical and mineral content
  - Characterizing terrain and geology

- **History of Mars prospecting/exploration**
  - Viking
  - Mars Global Surveyor
  - Mars Odyssey
  - Spirit
  - Opportunity
  - Mars Reconnaissance Orbiter
  - Phoenix
  - Curiosity

- **History of other prospecting**
  - Hayabusa
  - OSIRIS-REx
  - Rosetta and Philae
- **Upcoming missions to prospect**
  - RESOLVE
  - ARRM
- **Future prospecting needs**
  - Water near human landing site
  - Water accessibility

What do we test?

- **Civil engineering**
  - – Moving regolith and building berms
  - – Sintering landing pads
- **Consumable and Propellant Production**
  - – Oxygen production
    - Carbon dioxide electrolysis (Mars 2020: 22 g/hr O2 over 50 sols)
    - Oxygen liquefaction and storage (Mars Pathfinder: ~0.5 kg/hr)
  - – Methane production
    - Water acquisition and electrolysis
    - Sabatier reaction
    - Methane liquefaction and storage
  - – Trash to propellant
- **Manufacturing**
  - – 3D printing
  - – Creating feedstock
  - – Metalworking

Where do we test?

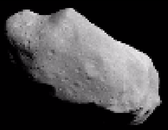
Microgravity Processing & Mining

1 ISS & Space Habitats

ISRU Focus
- Trash Processing into propellants
- Micro-g processing evaluation
- In-situ fabrication

Purpose: **Support subsequent robotic and human missions beyond Cis-Lunar Space**

2 Near Earth Asteroids & Extinct Comets



ISRU Focus
- Micro-g excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- In-situ fabrication & repair
- Trash Processing

Purpose: **Prepare for Phobos & future Space Mining of Resources for Earth**

4 Phobos

ISRU Focus
- Micro-g excavation & transfer
- Water/ice and volatile prospecting & extraction

Purpose: **Prepare for orbital depot around Mars**

Planetary Surface Processing & Mining

3 Moon

ISRU Focus
- Regolith excavation & transfer
- Water/ice prospecting & extraction
- Oxygen and metal extraction
- Civil engineering and site construction

Purpose: **Prepare for Mars and support Space Commercialization of Cis-Lunar Space**

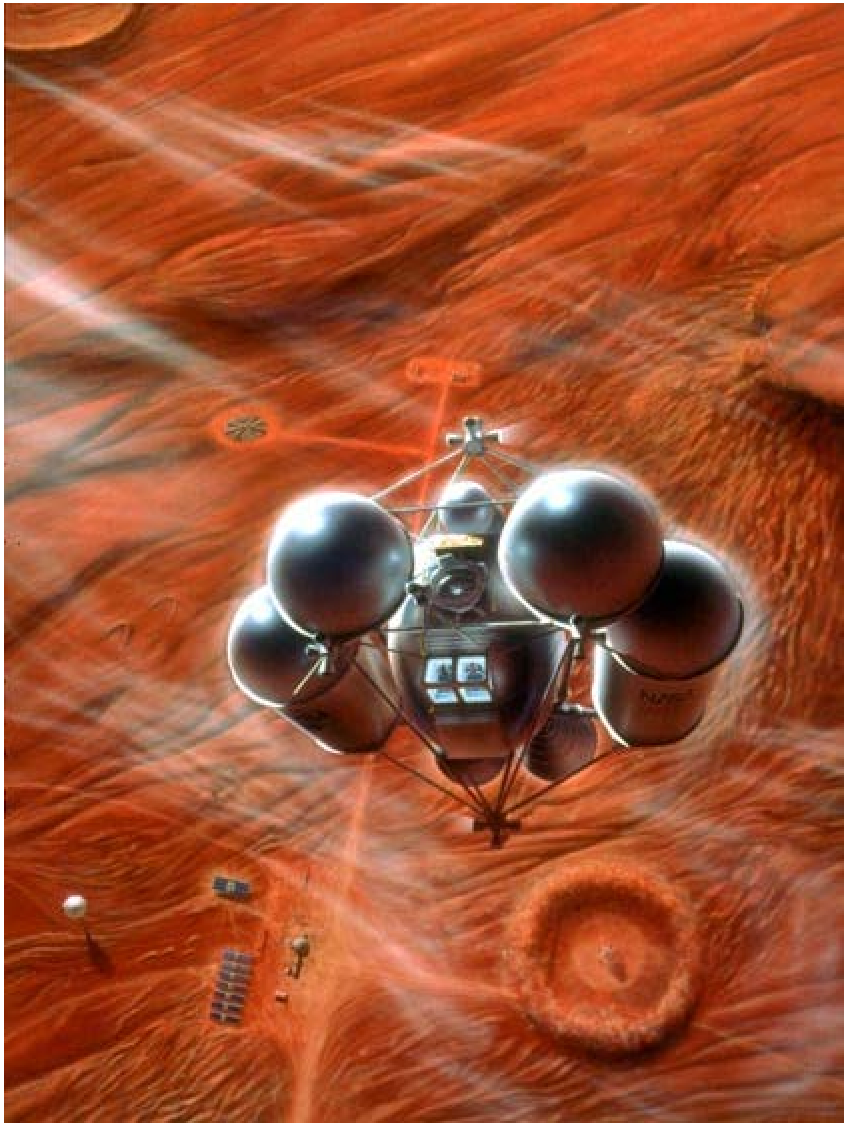
5 Mars

ISRU Focus
- Mars soil excavation & transfer
- Water prospecting & extraction
- Oxygen and fuel production for propulsion, fuel cell power, and life support backup
- Manufacturing & Repair

Purpose: **Support human Mars missions**

Utilization in the EMC

- **Mars Ascent Vehicle propellant production**
  - Replace 20-23 t of O_2 with ~1 t of ISRU system
  - Pathway to all propellant production (CH_4 + O_2)
- **EMC Architectural and Campaign Impacts**
  - ISRU power requirement
    - **Amount** of product (20-23 t)
    - **Time** to produce product (1.5-3 years)
  - Launch and Landing
    - Landed with MAV and integrated into descent stage
    - EMC studying distance of power system
    - All production complete prior to crew **landing** (DRA 5: crew **departure**)



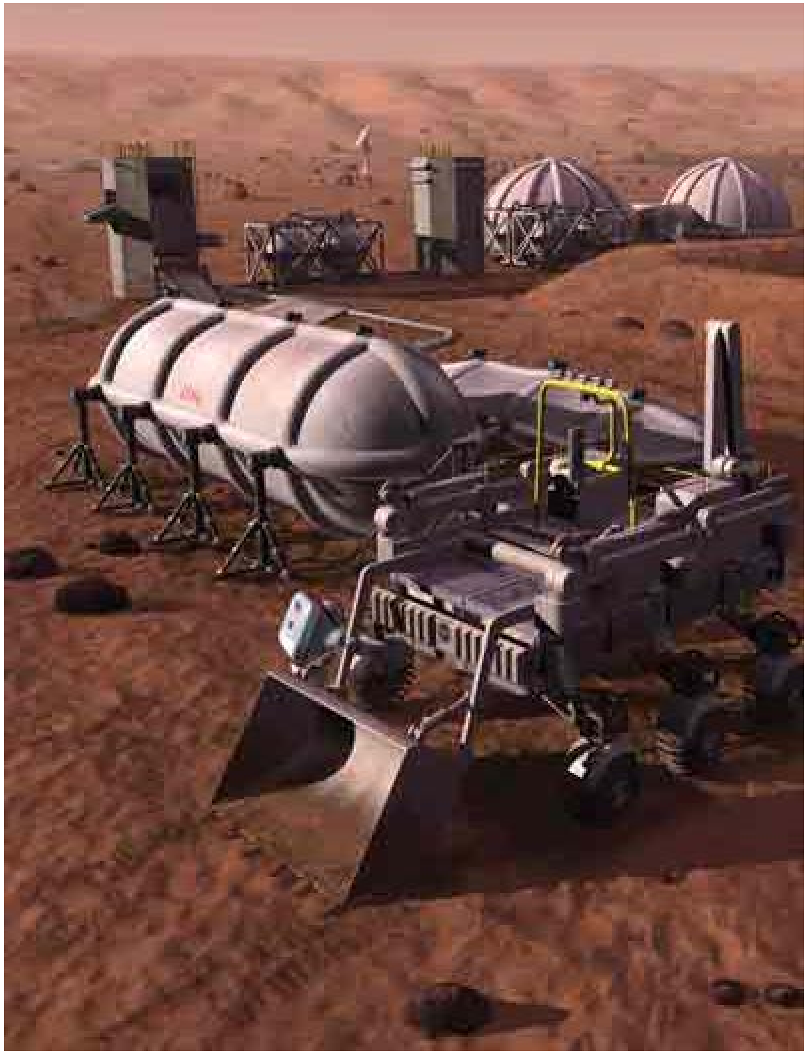
Utilization Beyond EMC—What could be?

- **Transportation architectures and their impact**
  - Vehicle masses, payloads, energy requirements
  - Propellant nodes: Moon, NEA, Phobos
- **Commercial resources and their impact**
  - Deep Space Industries
  - Planetary Resources
  - Shackleton Energy Company
- **Reusable systems**
  - Fuel cells for mobile power
  - Hoppers for surface mobility and sample return
  - Landers for transporting payloads

Surface Pioneering and Earth Independence

- **Consumables and Logistics**
  - EVA oxygen and water
  - Food
  - Packaging and clothing
- **Civil engineering**
  - Excavation
  - Regolith sintering
  - Construction
- **Metalworking**
  - Surface mobility
  - Habitation
  - Spares and replacements

The first missions to Mars will be used to prospect and test more advanced ISRU.



Current and Forward Work

- **Architectural trade of CH_4 + O_2 vs O_2 only**
  - Location
  - System requirements (*Mars regolith study*)
  - Integration
  - Testing and implementation
- **Pioneering trades**
  - Moon, NEAs, Phobos
  - Prospect/test/utilize analysis
  - What does a pioneering campaign look like?
- **Mars Human Landing Site Study**
  - Balancing science and human requirements
  - How to evaluate a site for ISRU

Questions?